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# Current state of photoconductive semiconductor switch engineering

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ABSTRACT

This paper presents the current state of a photoconductive semiconductor switch engineering. A photoconductive semiconductor switch is an electric switch with its principle of operation based on the phenomenon of photoconductivity. The wide application range, in both low and high-power devices or instruments, makes it necessary to take design requirements into account. This paper presents selected problems in the scope of designing photoconductive switches, taking into account, i.e. issues associated with the element trigger speed, uniform distribution of current density, thermal resistance, operational lifespan, and a high, local electric field generated at the location of electrodes. A review of semiconductor materials used to construct devices of this type was also presented.



**Contents**



## 1. Introduction

A PCSS (*Photoconductive Semiconductor Switch*) is an electrical switch with its operating principle based on the phenomenon of photoconductivity. When compared to classic switches, PCSSs are characterized by better properties including, i.e. optical coupling of control circuits, compact geometry, low switching jitter, faster rise and fall times, lower inductance, high switching frequency [1]. PCSSs are made with the use of highly-resistivity semiconductor materials. Depending on the used photoconductive substrate and the design of the switch itself, the operating voltage of an open switch may reach 100 kV and the forward current might be in the range of 1 kA [2], hence, these switches may find their application in high energy processing instruments, including directed energy pulse generators for HPEM (*High Power Electromagnetic*) weapons.

The wide application of the switches, in both low and high energy devices or instruments, make it necessary to consider, i.e. operating conditions. The property, important in low-energy applications, in information processing and control systems, will be the speed of the element triggering, as well as minimization of its dimensions, while in the case of high-energy applications – uniform current density distribution in the switch and its thermal resistance. The parameters of such devices depend on a number of physical phenomena occurring during its operation, which in turn limit the possible switch performance. The paper presents the operating idea of a photoconductive switch, supplemented with a review of semiconductor materials used as a substrates for

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such devices. Furthermore, we present selected issues in the scope of designing of photoconductive switches, extended by methods enabling the limitation of their negative impact on the operation of PCSSs, hence, improving output parameters of the devices.

## 2. Switch design and operating mode

PCSS is made of a semiconductor material with metal contacts placed on it which enable connecting the material to an electrical circuit. The area between the contacts is called a switch gap. The idea of operation of such a device and an example of a photocurrent path are presented in Figs. 1 and 2, respectively. The switch is excited by an optical signal, with energy higher than the bandgap energy of a given material, resulting in an increase in charge carriers concentration which causes a decrease in the semiconductor material resistivity, even by several orders of magnitude. In practice, the switch can be of various geometry which indirectly impacts the operating parameters of the entire device. As a consequence, the thickness of the switch should be equal to or higher than the depth of optical absorption, in order for the entire optical energy to be absorbed by the semiconductor material. The length of the switch depends on dielectric strength of the semiconductor material while its width is determined by the maximum current density. In addition, the switch geometry is also dependent on the method of an optical signal input to the device and the photoconduction operating mode used.

PCSS may operate in two modes: linear and non-linear. In a linear (conventional) mode, one absorbed photon generates one electron-hole pair. After lighting is switched off, thermal emission processes of carriers from deep defect centres take place, as well as recombination processes of charge carriers which recover the properties of the semiconductor material to the state prior to illumination. Within this mode, charge carriers are generated on the basis of intrinsic absorption (direct, bands-related) or extrinsic absorption (indirect, dope-sites-based). Photon penetration depth depends on the absorption factor of the used semiconductor material for the adopted wavelength and may reach tens of microns for direct transitions and a few microns for indirect transitions. In the case of intrinsic absorption, level the optical energy can reach is very small – in the range of tens of microns. As a result, optical energy density should be in the order of a few mJ/cm$^2$, so that it can lead to a reduction in the switch resistance. As a consequence, switches of this type are most often designed in side geometry as shown in Fig. 1b) [2]. In the case of extrinsic absorption, the optical energy may penetrate very deep areas, depending on the used dopants and their concentration. This operating mode allows designing (matching) the optical signal penetration depth, hence dimensions of conductive areas of the switch, via controlling concentration of dopants introduced into the semiconductor. Moreover, absorption of this type provides possibility to select the wavelength of incident light.

Excitation in the linear mode is independent of a value of the electric field generated along the switch. As a consequence, a PCSS may operate in only low-voltage circuits (electric field strength lower than 4 kV/cm). The switch current is largely concentrated on the surface of the semiconductor and surface flashover limits the maximum voltage at which a device may operate. Linear photoconductive switches are characterized by a longer operational lifespan, due to a decreased current density [2].

The non-linear mode, also called avalanche or high gain mode, occurs at a higher electric field. Charge carriers, excited by illumination, when present in a strong electric field gain additional kinetic energy and punch outer electrons into the conduction band which is called impact ionization and, as a consequence, manifests itself with an avalanche-type generation of charge carriers in the semiconductor material. It means that a photon may generate more than one charge carrier. An initiated avalanche process of charge carriers multiplication is continued until the moment, in which the field along the switch falls below a certain threshold, depending on the used semiconductor material (e.g., 4–6 kV/cm for GaAs). In this mode, the laser acts only as a trigger. If the electric circuit is able to provide the switch with sufficient power, it remains in the activated state, even after the laser pulse stops. As a consequence, this mode occurs only under a strong electric field along the switch.

The requirements regarding the pulse energy, in the case of a device operating in linear mode, were referred to earlier. In comparison, avalanche-based switches require smaller trigger pulse energies than linear-mode switches. For example, a linear PCSS, operating at 100 kV, in order to gain a resistance of 1 $\Omega$ in the closed state, requires a trigger light impulse with an optical energy equal to 25 mJ, while an avalanche switch, the energy equal to only 90 nJ (1 $J = 0.62415 \times 10^{19}$ eV). As a result, one photon in an avalanche switch may generate 100,000 times more charge carriers than in the same switch operating in a linear mode [3].

## 3. Application

The PCSS technology is being developed mainly due to the possibility of using this type of devices in many applications. Basic features creating the current wide interest in PCSS elements are the possibilities of their fast triggering (in the range of few nanoseconds) which is why they find their application in analogue-to-digital converter circuits, control and guiding systems. They can also be used in microwave and terahertz signal generators which operate under the direct conversion from direct current (*DC-RF*) [4]. More and more often switches are becoming basic elements in power electronics.

One of the examples of PCSS application is a hybrid power switch (Fig. 3) which consists of the fast mechanical switch $Z_1$ and a semiconductor power PCSS switch. The PCSS switch is attached to the fast switch $Z_1$ in parallel. This construction of the hybrid switch enables the fast switch to be closed on any moment of the voltage occurring between *a* and *b* terminals synchronously with the supply voltage. Properties of the described hybrid switch are similar to properties of an ideal switch. They ensure electric-arc-less switching at a minimal contact resistance in the on state and a visible insulation break in the off state.

PCSS are used with the purpose to increase efficiency of the device and switching dynamics, as well as values of currents and voltages. Advanced switching devices with a long operational lifespan will be crucial elements for LTD (*Linear-Transformer-Driver*) in next generation accelerators. Devices of such type use large amounts of switches [5,6]. Another application may be forming programmable pulse systems for dynamic material testing (Z-next, Genesis, THOR), efficient pulse systems for biofuels, short pulses (10 ns) for the Defence Threat Mitigation Agency (HPEM) and sprytron (fast-arc high-voltage and high-current switch) in nuclear weapons [7].

An interesting solution, widely described in the literature, is a compact semiconductor system, which is one of the main trends in the development of pulsed power technologies. It is inseparably associated with designing a perfect switch for application of this type. An example is a compact high-voltage pulse generator. It was constructed for use in a particle accelerator DWA (*Dielectric Wall Accelerator*) [8]. Accelerators of this type are a chance for next generation devices used in X-ray radiography and proton therapy. Such a device enables the acceleration of protons to high velocities and directing their beam inside the body of a patient. Each DWA module consists of semiconductor planar Blumlein lines SPTL (*Solid-state Planar Transmission Lines*), PCSS, laser diode operating as a trigger,

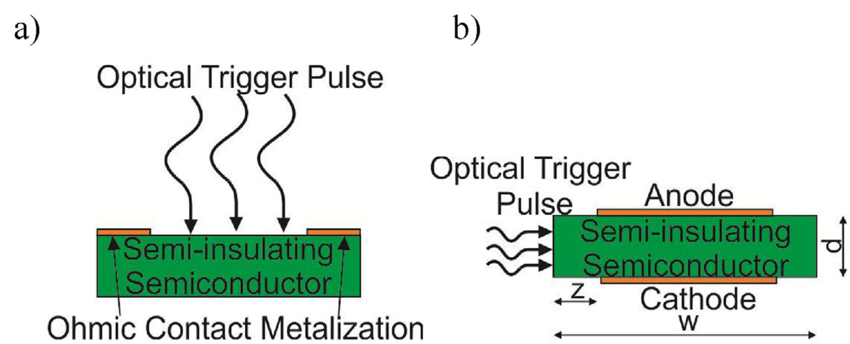


**Fig. 1.** PCSS idea of operation, taking into account different geometry of contacts' arrangement and varying location of PCSS photoconductive substrate illumination (left: lateral geometry, right: vertical geometry).

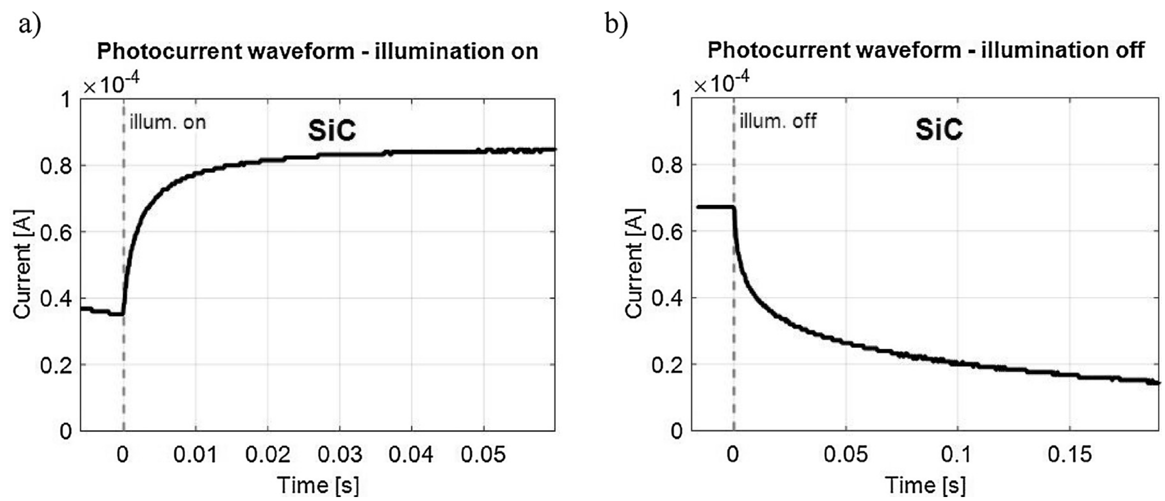


**Fig. 2.** Relaxation time waveforms of the current flowing through a sample of a material made from SiC: a) measured when triggering the illumination and b) deactivating the illumination. The sample was illuminated with blue light with a wavelength of ca. 440 nm. The gain factor of the current-voltage converter was of $10^7$ V/A. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

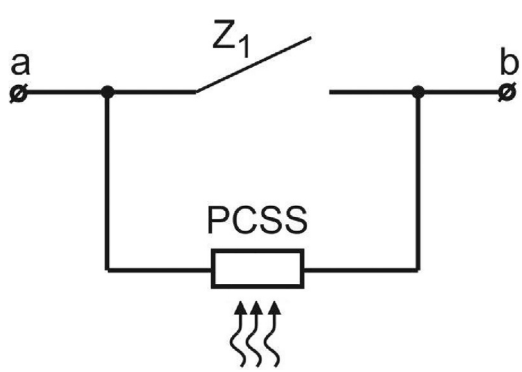


**Fig. 3.** PCSS application to the Hybrid Power Switch.

synchronous trigger system, and external power supply source. A DWA is a compact pulse device, in which the pulse creating lines, switch and vacuum wall are integrated into one, compact geometry. The results achieved for such a configuration allows reaching an output voltage amplitude in the range of 300 kV, the FWHM (*Full Width at Half Maximum*) of 10 ns, and a rise time of 3 ns [8].

### *3.1. Materials*

The substrate of a photoconductive switch may be a semiconductor material from a variety of high-resistivity materials, depending on their properties. The advancing semiconductor technology was the main determinant of the materials used for manufacturing such devices over the years. The parameters of basic materials which can be used to make a PCSS are summarised in Table 1.

The first designs of semiconductor photoconductive switches used mainly silicon. Low resistance, high value of dark current, long recombination time (>10 μs) preventing quick opening of the device and a number of other phenomena made silicon PCSS able to maintain high electric fields up to several microseconds, and as a result, the switch could operate in the pulse mode only [2]. Moreover, the optical absorption depth for this material is low, resulting in the fact that charge carriers are forced to flow in a very thin material area, directly below the surface of the switch (for silicon, the absorption depth is of 1 mm for a radiation wavelength of 1 μm) [2].

Over time, the attention of the designers was directed at materials with a wide energy gap (GaAs, InP, GaN), which are characterized by better parameters, i.e. critical value of the electric field, thermal conductivity or electrons velocity, which, in turn, makes materials of such type more attractive in applications involving high power, high voltages, strong electric fields and high temperatures.

It is worthwhile to analyse the parameters of individual semiconductor materials in the context of their application for the construction of PCSS devices. The electrons mobility and the electrons saturation speed determine the speed of charge carriers movement in a semiconductor. Electrons mobility is decisive for minor field strengths, while the saturation speed of charge carriers

**Table 1**
Selected parameters of semiconductor materials used for the construction of photoconductive switches [2].

| Material | Si | InP | GaAs | GaP | GaN | 4H-SiC | 6H-SiC |
|---|---|---|---|---|---|---|---|
| Bandgap energy [eV] | 1.11 | 1.34 | 1.42 | 2.26 | 3.39 | 3.23 | 3.0 |
| Critical electric field [MV/cm] | 0.3 | 0.5 | 0.4 | 1.0 | 5.0 | 3.0 | 3.0 |
| Mobility of electrons/holes [cm$^2$/Vs] | 1400/450 | 5400/200 | 8500/400 | 250/150 | 1000/200 | 900/120 | 400/90 |
| Thermal conductivity [W/cmK] | 1.3 | 0.68 | 0.45 | 1.1 | 1.3 | 3.7 | 4.9 |
| Thermal velocity of electrons/holes [10$^7$ cm/s] | 2.3/1.7 | 3.9/1.7 | 4.4/1.8 | 2.0/1.3 | 2.5/0.5 | 1.9/1.2 | 1.5/1.2 |

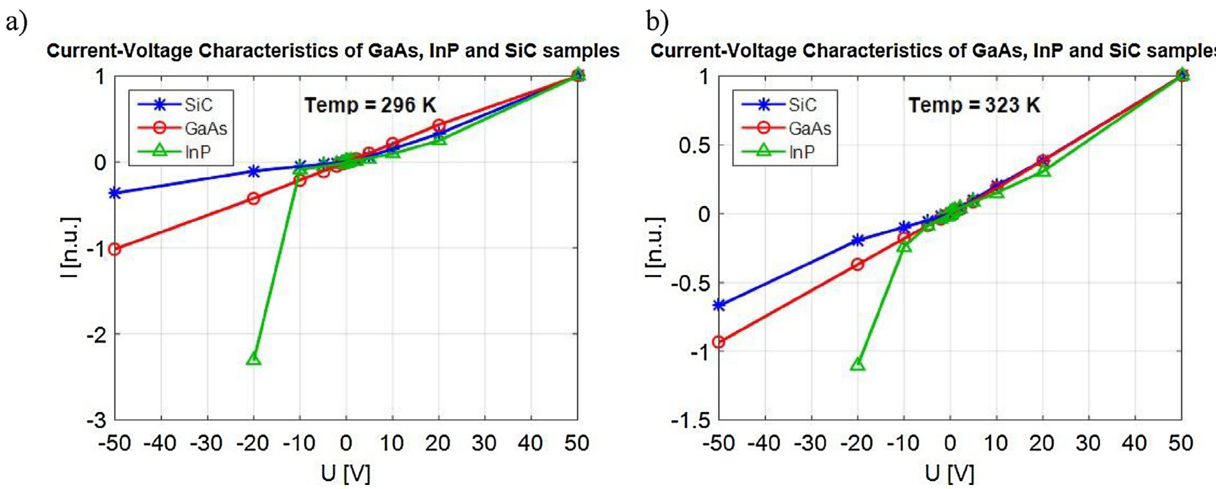


**Fig. 4.** Impact of ohmic contacts on the material conductance measurement. Current-voltage characteristics of three material samples: GaAs, InP and SiC measured for voltages from −50 to +50 V at two different temperatures: a) $T_1$ = 296 K and b) $T_2$ = 323 K. Values of currents were normalized to ±1.0 in relation to the absolute maximum value. Maximum currents for a temperature of 296 K at $U$ = 50 V: GaAs: 0.110 µA; InP: 0.038 µA; SiC: 21 pA. Maximum currents for a temperature of 323 K at $U$ = 50 V: GaAs: 1.10 µA; InP: 0.22 µA; SiC: 14 pA.

is the value decisive in the case of large strengths. Another parameter, which needs to be mentioned, is the thermal conductivity of a material which impacts heat discharge [9]. In the context of selecting a semiconductor material as a substrate of a photoconductive switch, the value of the electric field defined for those materials below which avalanche multiplication of charge carriers does not take place, hence, the device cannot operate in a non-linear mode, needs to be mentioned. For example, avalanche multiplication in silicon and gallium phosphide does not appear below 200 kV/cm, which is why these materials operate almost exclusively in a linear mode. In the case of GaAs and InP, this process may take place for a field strength higher than 4–6 kV/cm and 15 kV/cm, respectively. The absorption depth which determined effective thickness of the photoconductive semiconductor material is also worth mentioning [2].

The main problem of PCSSs is a short lifespan resulting from voltage and current overloads. Other materials began to be used for constructing switches along with technological development. A very important parameter of the material used for photoconductive switch construction is its dielectric strength, which is the highest value of the electric field, which can exist in the material without forcing breakdown.

This reason is the main factor behind a growing popularity of silicon carbide (SiC) – the critical value of electric field for this material is ca. 3 MV/cm. There are many crystallographic varieties of silicon carbide, but 4H and 6H are most widely used. Experiments show that it can operate at high electric field in the range of 25–56 MV/cm. For comparison, GaAs may operate at an electric field in the range of approximately 250 kV/cm. Very high dielectric strength of silicon carbide allows the use of very thin layers of this material, while operating at high voltages. In addition, this material is characterized by a very high thermal conductivity factor (value comparable to a copper). For comparison, thermal conductivity of GaAs is only 10% of SiC. In addition, switches made from silicon carbide are characterized by quick regeneration (back to normal state), high thermal and chemical stability and the possibility to operate in temperatures up to 600 °C and switching currents of 200 A [10]. As a consequence, parameters of silicon carbide as a semiconductor material present a chance to produce elements with very favourable properties, especially for use in power electronics. Over the recent years, its use has become more feasible, mainly due to the constant technological development, leading to a gradual decrease in prices of silicon carbide elements and commercial availability of substrate wafers made from this material [9].

Gallium nitride (GaN) has become a second, equally popular material over the recent years. It is a material with the widest bandgap. This feature makes devices manufactured basing on the material able to operate at high temperature ranges and characterized by a large critical value of the electric field at ca. 5 MV/cm, much higher than of silicon or gallium arsenide. It makes large miniaturization of devices manufactured on the basis of GaN possible. Due to the carriers' high drift velocity, which is approximately $2.5 \times 10^7$ cm/s, gallium-nitride-based devices can operate at very high frequency ranges [11]. It is anticipated that it is gallium nitride which, in the nearest future will replace silicon as the primary semiconductor for PCSS. An important feature of this material isa high thermal conductivity and thermal stability of electrical properties. GaN is also resistant to aggressive environment and ionizing radiation. Moreover, this material has a very high melting point (approximately 2500 °C) [2,12]. Unfortunately, this fact makes the production of gallium nitride crystals with the use of a classic Czochralski or Bridgeman method impossible and their manufacturing technology is still under research. Manufacturing technologies include mainly individual crystals and the growth process is very slow, expensive and requires high operating temperatures [12,13]. In addition, this process is difficult to control which leads to the formation of crystals with many imperfections, such as "tubes", inclusions, impurities or other defects, decreasing the usefulness of the material. Currently there are two methods of PCSS fabrication based on GaN material. One of them exploits the material as a bulk semi-insulating material being the substrate itself. Since it is quite difficult to find all required properties in a single material, which could be economically used in the PCSS fabrication, there are few companies that use the GaN material for this purpose. For example, Kyma Technologies is producing gallium nitride using own patented processes for manufacturing GaN-based switches [14,15]. Their thick bulk GaN substrates are grown by HVPE (*Hybride Vapor Phase Epitaxy*) using a doping scheme which results in a dark resistivity >$10^9$ Ω/cm. Experiments utilizing this material can be found, inter alia, in the following papers [15,16]. Unfortunately, residual donor impurities and native defects of the material cause the GaN-based PCSS, which becomes a strong n-type, to be very leaky. To increase the resistivity of HVPE GaN acceptor-like dope impurities are usually introduced. The most used dopant is Fe [17] which extremely shortens the effective carrier lifetime (down to ~10 ps) and allows reducing leakage currents [18,19]. As a result, PCSSs based on GaN:Fe could feature a fast recovery time which is highly desired in pulse power applications [16,18,20].

The second method of the PCSS fabrication is to grow GaN epitaxial layers on a substrate. The Fe dopants can also be used in this case, but as it is known, the Fe dopants have a strong memory effect which leads to redistribution of Fe into subsequent epitaxial layers, and have a limited range of possible doping levels. On the other hand, Fe dopants are desired as they improve the semi-insulating properties of GaN layers by creating deep electron traps ($E_C$ – 0.9 eV) and deep hole traps ($E_V$ – 0.9 eV). Unfortunately, these traps are characterized by long time constants what manifests itself in devices as current collapse. In the latest publications authors show high-voltage lateral GaN PCSSs with fast response time that have high resistivity using uninteintionally doped semi-insulating GaN grown on a SiC substrate by MOCVD (*Metal Organic Chemical Vapour Deposition*). The off-state breakdown voltage achieved (>4 kV) was limited by the thickness of the GaN epitaxial layer which was just of 1.4 μm [21]. This kind of experiments shows a promise for PCSSs with fast response time for applications requiring high repetition rates.

### 3.2. Selected issues

PCSSs parameters depend mainly on the properties of the material the photoconductive substrate of the device is made from. Apart from aforementioned properties, researchers increasingly concentrate on parameters, such as: the number of unfilled defect centres levels and their activation energy level in comparison to the bottom level of the conduction band which impact the voltage hold-off. Parameters of unfilled defect centres levels (concentration, activation energy) determine the voltage hold-off and the leakage current in a PCSS [22]. A material parameter which determines the effectiveness of photocurrent in a PCSS is the carriers lifetime associated with recombination processes. The lifetime also indirectly impacts PCSS's dynamic processes, thus, the operation speed of a switch, defined by its turn-on and turn-off times. Currently, the authors are conducting simulation-based research on the properties of materials used for manufacturing PCSSs. These studies are associated with determining the defects concentration and the defect structure of selected materials with a wide energy gap and its impact on the operation of photoconductive switches [23–26].

Apart from the properties of the switch substrate itself, there is a number of additional physical phenomena undergoing during the operation in high-voltage and high-current ranges which adversely affects the performance of the switches. This subsection presents selected issues, associated with the operation of photoconductive switches, supplemented with methods, which allow for the reduction of their negative impact on the operating results of such devices.

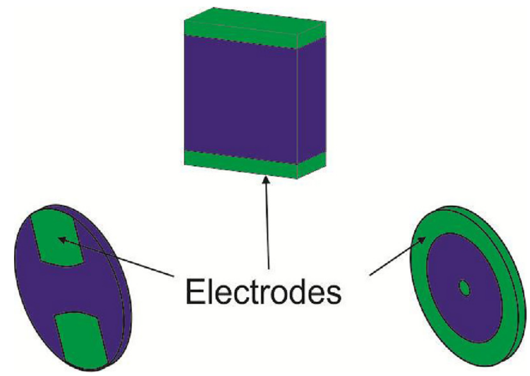


**Fig. 5.** An exemplary location of ohmic contacts in a PCSS [27,28].

#### 3.2.1. Ohmic contacts

Contacts are metallic layers formed on the structure surface of a device, in order to ensure current conductivity current flow. Forming ohmic contacts creates a metal-semiconductor (*m-s*) junction. Such a junction should be of a linear nature in order not to influence the properties of the tested material. It is particularly important in applications for low-current analogue systems. It should be also characterized by a relatively low resistance, independent of the voltage-bias direction and, in addition, parameter stability during long-term operation at high temperatures. In the case of high-power devices, forming high-quality ohmic contacts is a crucial factor, since the reliability of those devices depends largely on the quality of ohmic contacts. For materials with a wide energy gap it is an extremely difficult task. The current-voltage characteristics of three semiconductor material samples (SiC, InP, GaAs) were measured in the dark, at two different temperatures ($T_1$ = 296 K, $T_2$ = 323 K), and their non-linearities were identified, which can be associated with non-linearity of ohmic contacts. As can be seen in Fig. 4, it is not always possible to produce ohmic contacts with the desired properties. Measurements of the sample made of GaAs indicate the linearity of metal-semiconductor junctions forming its ohmic contacts, while the measurements for the remaining two samples, indicate the non-linearity of formed metal-semiconductor junctions. Non-linearity of ohmic contacts impacts the accuracy of determining the resistance of the material sample itself (if relevant), since it depends on the measurement voltage and the lower the sample resistance, the higher the impact, meaning high currents during illumination (switch triggering). Despite an entire domain of science devoted to the contacts, starting from the physics of a metal-semiconductor junction and ending with the technology of specific contact formation, very often these contacts are the main reason of the degradation of the entire device which is linked to the electro-migration of the contact metal towards an active area that may lead to a short-circuit or increasing the degree of non-radiation recombination [27].

Location of contacts in a PCSS directly impact the parameters achieved by these devices. Moreover, their location indirectly determines the active surface of a semiconductor material absorbing radiation in a switch. First implementations of photoconductive switches focused on a simple structure of ohmic contacts. Selected implementations are shown in Fig. 5 [27,28].

Mechanisms associated with the destruction of ohmic contact structure result, in the first place, from the formation of discontinuities within the contact layers. This phenomenon becomes apparent for selected PCSS designs. This non-linearity is linked to sudden changes in the electric field strength, generated on the

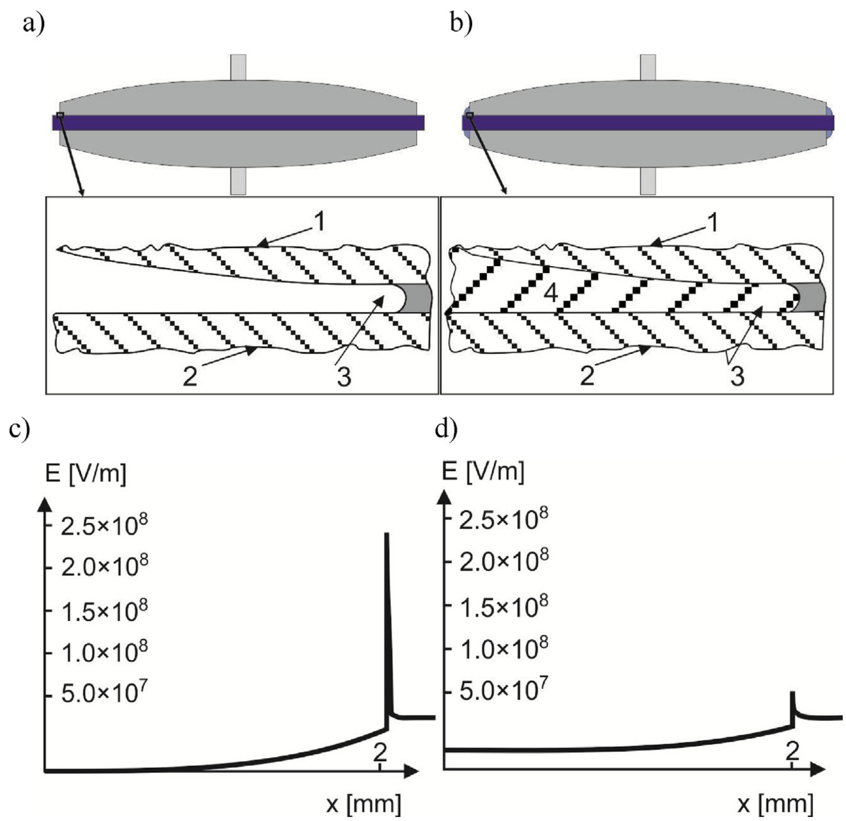


**Fig. 6.** a) An example of a PCSS design with an exposed meniscus (1) forming between the electrode (2) and the semiconductor material (3); b) filling the gap between the electrode and the substrate with a material with high permittivity (4); courses of change in the electric field strength on the border between the electrode and the semiconductor material (3): c) in the case of no filling and d) with the gap filled with a material with high permittivity [29].

border between the electrode and substrate surfaces. A so-called *contact meniscus* (Fig. 6) is formed between these two surfaces. A mechanism of such type makes even silicon carbide, which is characterized by high resistance to strong electric fields, to be prone to damage as a result of a breakdown, which is why, scientists are looking for ways of mitigating the aforementioned problem. Another process is the occurrence of the flashover phenomena, caused by high strength of the electric field on the surface of the switch, hence, limiting the maximum voltage at which the switch may operate.

The existing methods of mitigating these phenomena concentrate mainly on modifying the contacts geometry. One of the ways is filling the gap between the electrode and the substrate with a material with a high permittivity (Fig. 6) which subsequently reduces the rapid nature of the changes in the electric field [30]. Other methods include, i.e. forming a concave surface and convex electrode, which results in direct contact of these areas. Moreover, in worldwide literature, we can come across the use of so-called liners, located directly in the substrate, at the contact points of the surface between the substrate and the electrode or on substrate edges. The material used for the liners should be one with high permittivity or either a conductor or semiconductor. Using such a layer allows to apply a high electric field onto it. This layer may be formed as a doped sub-surface layer of the substrate, spreading along the substrate to a depth of ca. 1 $\mu$m [30]. Optionally, the substrate should be multi-layered with a minimum of two photoconductive layers separated with a layer consisting of a conductive or semi-conductive material. These elements enable profiling and aligning the electric field along the borderline areas and separating the electrode from the substrate. Selected implementations of these designs are shown in Fig. 7 [29].

Another aim of designers is to limit and mitigate the mechanisms which lead to damaging the semiconductor material of which a switch is made. The first studies concentrated on placing additional passive layers on the substrate in a gap between the electrodes of the switch. As a consequence, this layer guaranteed an increase of the switch off-mode resistance [30]. Other concepts focused on utilizing additional semiconductor and isolator layers in order to increase the dielectric strength of the switch material [28]. It is important to stress the fact that dielectric strength allows to decrease the switch thickness, which, in turn, enables a reduction of the optical energy required to close a switch, linearly proportional to the square of the switch thickness [28]. Using highly doped semiconductor materials serves as a conductive layer, which reduces the injection of carriers onto the surface of the switch's electrode. Moreover, these layers are used to break and disperse spot burnouts occurring due to breakdowns, which otherwise lead to the formation of filament current paths [28].

Another method, presented in 2001, was the formation of doped structures in the areas under the switch contacts (Fig. 8) [31]. Doped layers with high concentration of charge carriers in the contact areas reduce energy density in the contacts through removing common impact ionization. These zones separate the areas between the channel and the contacts, so that they enable reducing a high electric field near the contacts. At the same time, this allows for the formation of paths close to the contacts, as a result of current spreading over these areas. Moreover, this method allows to transfer the termination point of a current path from the metal–semiconductor area to the doped semiconductor–semiconductor area, which is less prone to damage. This concept enabled an increase of the device's lifespan to a value above 100 million switches [31].

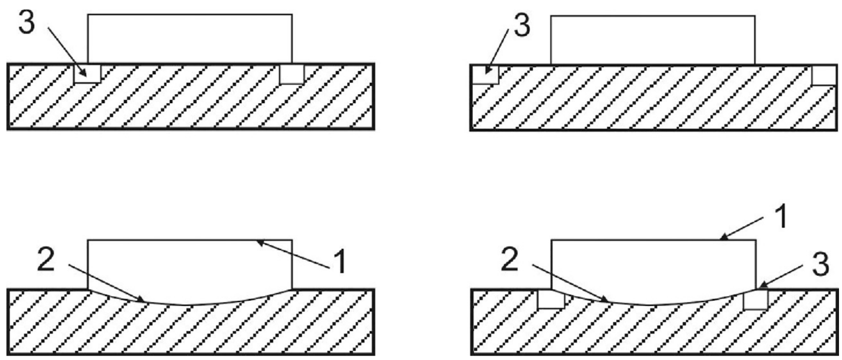


**Fig. 7.** Selected implementations of PCSS design, allowing the reduction of electric field surges on the borders of electrode-substrate areas; 1 – convex electrode, 2 – concave substrate, 3 – additional structural elements (liners) [29].

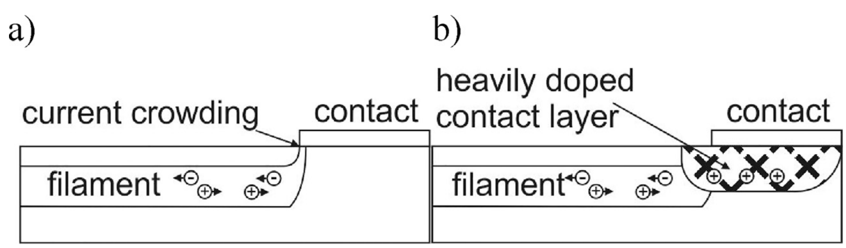


**Fig. 8.** a) The phenomenon of current crowding under the switch contacts, b) elimination of the phenomenon of current crowding under the switch contacts by forming tailored doping profile zones under the switch contacts [31].

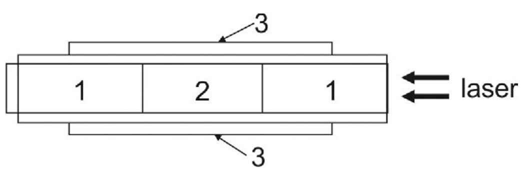


**Fig. 9.** The schematic idea of a PCSS design created from a substrate of which the central part is a photoconductive material (1), while the outer part is made of a non-conductive material (2), and the conductive electrodes (3) are formed on opposite sides of the substrate [33].

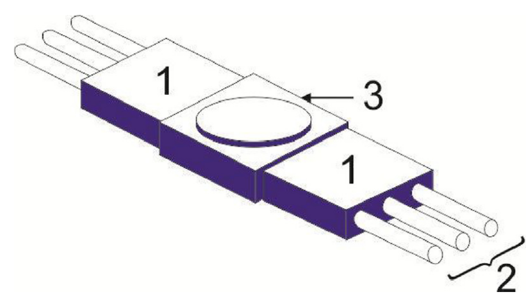


**Fig. 10.** A PCSS design using two waveguides (1) connected directly with the photoconductive substrate of the device (2) and with two sets of optic fibres (3) [34].

A variation of this method is the use of a thick, poorly conductive layer formed on the surface of a strongly doped layer. It causes the widening of the current stream (near the contact), since the additional (transverse) resistance levels voltage drops between different current paths formed between the switch gap and different points of the metal contact [32].

These methods, although they enabled the increase in switch lifespan, proved to be insufficiently effective when it comes to switching current in the order of magnitude of a single kiloampere (for pulse durations around 100 ns).

Another idea, presented by researchers in 2014, is a photoconductive switch formed from a substrate with photoconductive material as its central (1), while the outer part is made of a non-conductive material (2) A schematic diagram of the design is shown in Fig. 9. Conductive electrodes (3) are formed on opposite sides of the substrate and they stretch outside of the central part of the substrate, with their edges located on the outer part of the substrate. As a consequence, an electric field generated on the electrode edges lays on the outside, thanks to that it is isolated from the central part, which is an active switching element of the device. Light is sent via the outer part to the central part of the switch in order to trigger it. The material used for constructing should be characterized by the following properties: high resistance to breakdown in relation to the material filling the central part of the substrate, optical transparency (for the triggering light), and good thermal conductivity in order to remove excess heat from the central part of the substrate. Optimally, this material should not be photoconductive, as a result of which, the active part of the device has the option to manipulate and control the electric field on the edges of the electrodes and direct light to the active part of the switch [33].

Another interesting solution suggested by the scientist is separating the photoconductive material with a high-strength material and simultaneous dielectric encapsulation (closing them in a separate structure). In addition, the authors used a special structure for light introduction to the PCSS, which involves connecting a waveguide (1) (directly to the photoconductive wafer or substrate of the device) and attaching any number of optic fibres to it (2), as seen in Fig. 10. Consequently, only metallic contacts (3) and the surface of optical signal introduction (2) are exposed to the impact of external factors [34]. The electric field in this case may smoothly change thanks to the use of dope gain points along the edge of the conductive layer, by creating electrically resistive layer on the encapsulation surface, in order to encapsulate (using the resistive layer) the conductive layer.

Furthermore, it is also possible to use different optical systems, in order to transmit the optical signal to the device: from single to double light input surfaces, through direct waveguide connection, to using open channels, through which light can directly reach the photoconductive substrate, and using a cylindrical switch structure

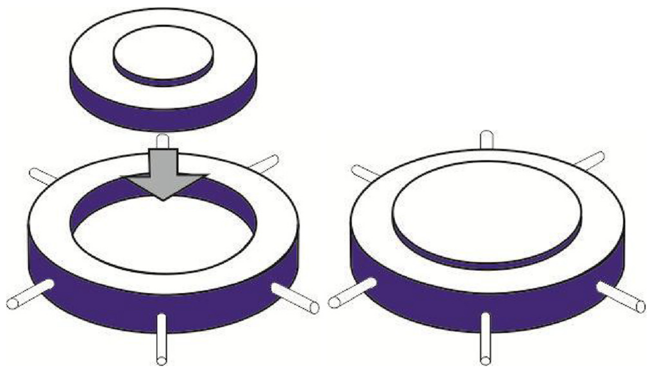

**Fig. 11.** The encapsulated structures of a cylindrical switch [34]. a) Into a ring-like waveguide with evenly distributed optical fibres, installed is a cylindrical photoconductive substrate with two metallic layers forming ohmic contacts on the opposite sides. b) A slightly modified version of the switch involves expanded ohmic contacts overlapping with the waveguide.

(Fig. 11). In this case, the substrate is in the cylindrical form with upper and side surfaces. Ohmic contacts are placed on the upper and bottom surfaces of the cylindrical substrate. A heated photoconductive substrate is then installed into a ring-like waveguide, with its outer surface connected to the outer surface of the substrate, forming a waveguide-substrate connection. Optical fibres are distributed evenly around the waveguide [34].

New ideas appearing in the literature are solutions based on thicker metallization of electrical contacts with increased conductivity, by introducing an additional 700-nm-thick gold (Au) layer. Another option is the innovative vertical location of ohmic contacts. An expected result of such an approach is the separation and distribution of current paths over a larger contact area, which is supposed to decrease current density and increase the lifespan of the device [35] (Fig. 12).

The presented issues associated with the structure and execution of ohmic contacts, bring us closer to full understanding of the processes undergoing during the operation of the contacts, and allows the creation of better ohmic contacts with a satisfactory structure, which in consequence, will allow to obtain a device with the required parameters.

*3.2.2. Filament nature of current*

Another problem, which limits the operational capability of ohmic contacts is the very large density of the current flowing through the switch and the associated current dispersion phenomenon. It needs to be stressed that this process occurs only in the case of high-gain switch operation. However, researchers all over the world devote much attention to this mechanism, due to the fact that non-linear operation mode is dedicated to power electronic applications. During the charge carriers avalanche multiplication process, the so-called current filaments are formed. Consequently, current paths running between the switch contacts branch, causing current to propagate in the switch channel. The concept of the phenomenon is visually presented in Fig. 13. In selected cases, the width of a spreading (branched) current in a channel is in the order of magnitude of 15–300 μm, while the current density of a single path may reach value up to MA/cm$^2$ [2,36]. Average value of carriers concentration in current filaments range from $10^{16}$ to $10^{17}$ cm$^{-3}$. Locally, carrier densities may be from $10^{14}$ to $10^{19}$ cm$^{-3}$.

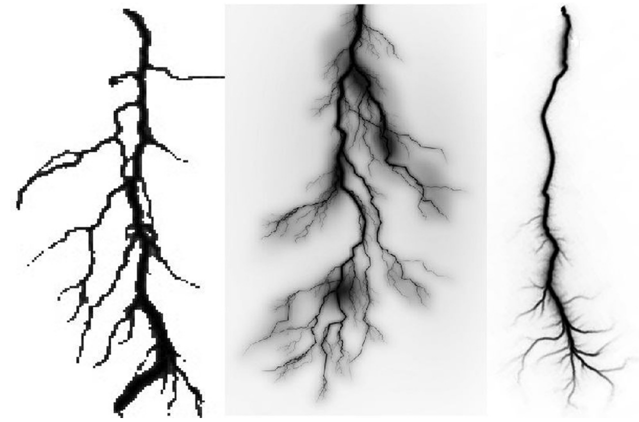

**Fig. 13.** Examples of current paths (high-gain operating mode of the switch).

High current density in the paths causes local heating and damage on the border of the switch contacts, every time the device is triggered. A consequence is the gradual erosion of contacts, which leads to a damage of the device. This mechanism leads to a drastic decrease in the lifespan of the instrument. As a result of this phenomena, it is necessary to limit the amplitude of the switched current and the pulse width, in order to ensure failure-free operation of the device. Currently, in some applications, the technological limit is the said lifespan of the switches. The easiest way to mitigate phenomena of this type is the operation of the switch in linear mode.

The morphology issue discussed earlier and the quality of ohmic contacts formation impact the course of PCSS current paths. The main solutions associated with improving the structure of ohmic contacts and the areas between the contacts and the semiconductor material, enable limiting current paths, thus providing a possibility of operation with a higher current density, which, at the same time, contributes to increasing PCSS lifespan.

Other concepts focus on methods of creating multiple parallel current paths along the switch gap, by interfering in the inner structure of the switch or using complex optical triggering systems of the switch. Selected solutions are presented below, providing a synthetic description of methods of mitigating this phenomenon during PCSS operation.

First experiments concentrated largely on limiting single path currents (for short pulses <100 ns), which in consequence, limited charge carrier density on the surface between the semiconductor material and the ohmic contacts. The reduction of a single path cur-

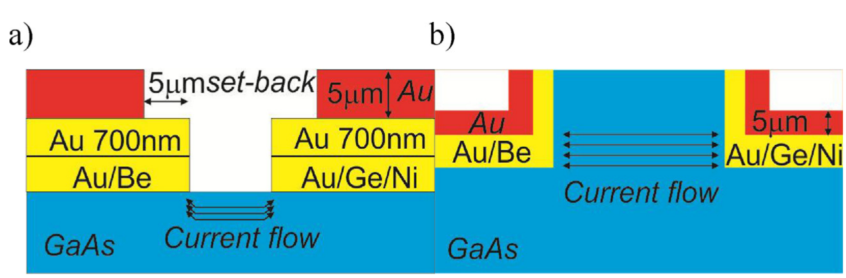


**Fig. 12.** Ohmic contacts' placing diagrams: a) application of an additional 700-nm-thick gold (Au) layer, b) innovative formation of the contacts, allowing for the minimization of current density and the thermal power output, as well as improving routine maintenance and the operational lifespan of the device [35].

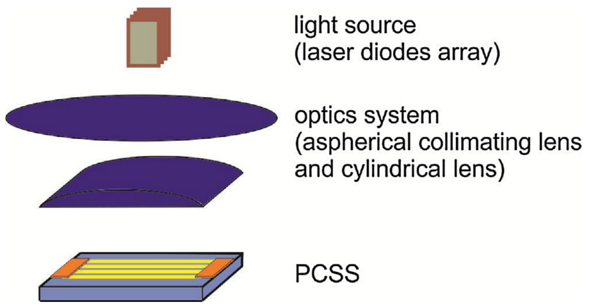


**Fig. 14.** The concept of multi-line switch triggering with the use of an optical system containing a stack of optical diodes, an aspherical collimation lens in connection with a cylindrical lens [36].

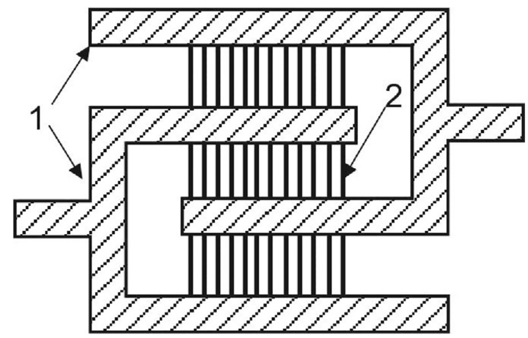


**Fig. 15.** The comb-like structure of PCSS contacts (1), enabling the generation of additional parallel current paths (2) [37].

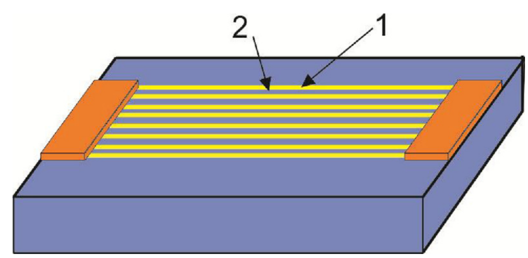


**Fig. 16.** The idea of dead spots (1) between current paths (2) in a PCSS gap [38].

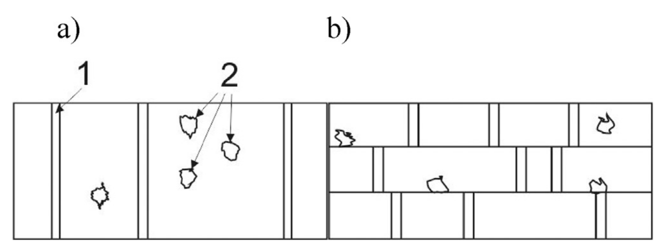


**Fig. 17.** Examples of a) semiconductor material imperfections and b) eliminating the problem by making a PCSS substrate in the cascade technology [29].

rent was achieved by dispersed illumination of the switch gap, near one of its contacts [37]. This technique allows for multiple parallel current channels to form which stay separated over the entire conduction process. Such triggering allows for a uniform current distribution along the width of the contact by sharing the current in multiple paths, hence, decreasing the damages near the contacts. Another possibility was to use glass rods as cylindrical lenses, in order to focus light from many optic fibres into lines along the switch. However, this method is characterized by differences in light intensity along single paths and differences between the paths [27].

In general, the presented solutions limited the total current density and required complex, expensive and ineffective processes of processing the laser beam into thin lines illuminating the switch surfaces.

Another approach was the change of the switch optical system structure. One of the methods is based on using a multi-line optical triggering, in order to generate multiple parallel current paths along the contacts. In general, the light source consists of a diode matrix in the form of a series of lines with laser diodes (*laser diode bars*). The additional optical system was equipped with an aspherical collimation lens, which in connection with a cylindrical lens precisely set the zoom factor and the shape factor in such a way, so that the laser light lines exactly fill the gap between the switch contacts (Fig. 14). Triggering of this type improves the ability to generate current paths, as a result of what, they are more consistent, direct and parallel than it is possible, when using dispersed or point triggering. The described mechanism creates eight separate current paths. In addition, it improves the lifespan of switches for high current operation, by increasing the number of current paths and decreasing current density in the contact electrodes in a controlled manner [37].

For example, after activating the device when switching currents in the order of 400 A, the current drop is only by 2% (after 100 activations), which is why effective operation of the device is possible. The same switch, for a current of about 90 A, causes a decrease by 28% (after 86 triggers) in the case of using a point light source.

Further improvement of the operational lifespan of the device was achieved by using the so-called comb structure of switch contacts. The structure allows for the generation of additional current paths without significantly increasing the complexity of the used optical system. Moreover, the method also allows each of the 28 light lines to illuminate many gaps (1) between the arms (fingers) (2) of two or more coupled electrodes (3) (Fig. 15). Using the same optics in the discussed example allowed to triple the number of generated current paths and for a more effective heat distribution in the device, without increasing the complexity of the optical triggering system [37].

One of the most modern solutions, from 2014, is using the so-called dead spots in the switch gap between current paths (Fig. 16). This space enables path formation and prevents current from flowing between adjacent paths. Areas of this type may be generated by introducing defects to the crystalline lattice, through implantation of high-energy ions. The length and width of the channels are designed in such a way, so as to ensure high quality of the switched current while extending the PCSS lifespan. Controlling the current path formation process reduces the density of maximum current, which, in turn, leads to a reduction in device damage [38].

### *3.2.3. Other issues*

Other issues arising during the PCSS engineering stage are the defects of semiconductor materials. These imperfections may include, i.e. micro-tubules (1), empty spaces (2) or cracks (Fig. 17). For example, micro-tubules are long empty tube-like spaces spreading along the entire length of the substrate. Changes in the substrate structure may also cause a number of adverse phenomena in the device's operation. This is why it is attempted to mitigate such phenomena by making a substrate in the cascade technology, which allows to isolate empty spaces and decrease the micro-tubule length [Fig. 17b)] [29].

It is also worth mentioning about the issue associated with the transparency of the material used as a PCSS substrate and the corresponding laser light absorption depth coefficient. If we consider switches operating simultaneously, in many cases their design may be uneconomical due to high prices of the semiconductor material. Additional dielectric layers causing complete internal light reflection are used in these cases, resulting in a decrease in

a) b)

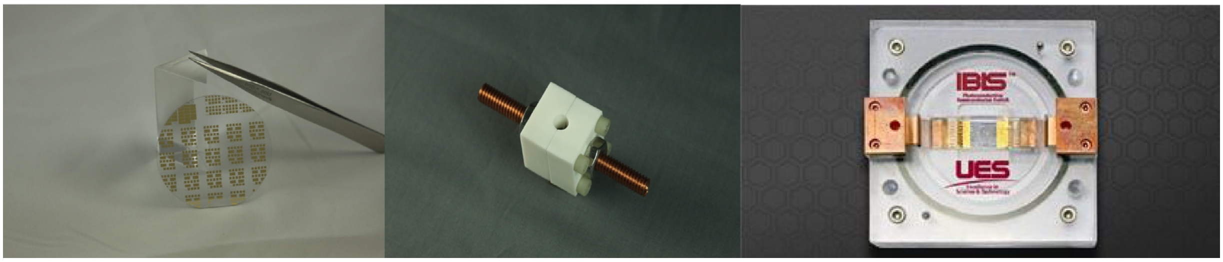


**Fig. 18.** Photoconductive semiconductor switches: a) Kyma technologies – wafer of the photoconductive substrate with several structures (left) and the switch's casing (right), b) UES Incorporation [39,40].

substrate dimensions, which in consequence, leads to a cheaper device and their geometry focusing on ensuring appropriate electrical parameters (e.g., current density). In the case of these projects, optical losses may be minimized by introducing light to the photoconductive substrate at an optimal angle (e.g., Brewester's angle). Furthermore, additional optical cover or coating may be used, in order to decrease the losses on the connection between two materials with different material coefficients (dielectric constant) [34].

## 4. Existing solutions

When analysing the market of commercially available devices of such types, two main solutions may be distinguished. The first one is the PCSS created by *Kyma Technologies* – Fig. 18a). The photoconductive substrate for this device is gallium nitride, produced by the same company, on the basis of their own technology, confirmed by a U.S. Patent [14]. The manufacturer indicates that the material is produced specifically for the needs of PCSS. Additionally, the materials provided by the company indicate that the offered switch is characterized by the highest voltage out of all gallium nitride based devices available on the market. The switch is designed to block up to 2000 V and to drive 40 A into a 50-ohm load at 80,000 W in power when turned on with an appropriate optical beam. The device reacts to electromagnetic radiation in the range of visible light. To to the gallium nitride bandgap width, ultraviolet range radiation is required, while the excitation by visible light takes place under the principle of external excitation. Kyma Technologies emphasises the switching speed as the main advantage of their switch. The tests performed by the manufacturer have shown these values to be smaller than 1 ns (values in the range of 18–200 ps were achieved). Moreover, studies over simultaneous connection of several switches are ongoing, which would allow the creation of a device with an operating voltage of 100 kV [39].

The second one is a switch manufactured by UES *(Excellence Science & Technology)* – Fig. 18b, utilizing gallium arsenide. According to the data delivered by the company, the IBIS PCSS supports voltage up to 75 kV and the total current in the range of 1 kA. Individual channel current has been measured at around 20 A/channel at 1 kA, with a rise time of 600–800 ps. The device has functional dimensions of just 1–2 cm per side, and can be triggered with low incident energies of 50–150 μJ/cm$^{2\cdot}$ [40].

## 5. Conclusions

The paper presents selected issues in the scope of designing photoconductive switches, taking into account a review of materials used to construct devices of such type. The main difficulties include issues associated with, i.e. manufacturing and geometry of ohmic contacts, element activation speed, minimizing its dimensions, equal distribution of current density, thermal resistance, operational lifespan, high local electric field generated at the ohmic contacts location, imperfection and transparency of the semiconductor material used as a photoconductive substrate for the PCSS. The synthetic review of phenomena occurring in an actual device presented in the paper, takes us closer to fully understanding the processes ongoing during the operation of such devices and, as a consequence, i.e. allows to select an optimum structure of the switch, taking into account the geometry of the ohmic contacts, light source and the material used as a photoconductive substrate, as well as the switch operating mode, in relation to a specific application.

The studies conducted by scientists are mainly aimed at constructing a switch, which would maintain high operating voltage, and, at the same time, allow for the flow of high current. Ensuring long operational lifespan and reliable operation is also required. All these tasks result in works that are still being conducted on developing a switch satisfying the required assumptions.

## References

[1] D. Mauch, W. Sulivan, A. Bullick, A. Neuber, J. Dickens., High power lateral silicon carbide photoconductive semiconductor switches and investigation of degradation mechanism, IEEE Trans. Plasma Sci. 43 (6) (2015) 2021–2031.
[2] J.S. Sullivan, Wide Bandgap Extrinsic Photoconductive Switches, in Lawrence Livermore National Laboratory Report LLNL-TH-640323, 2013.
[3] F.J. Zutavern, et al., Properties of high gain GaAs switches for pulsed power applications, Digest of Technical Papers, 11th IEEE International Pulsed Power Conference 2 (1997) 959–964.
[4] M.B. Kuppam, RF Signal Processing Using Ultrafast Optoelectronics Devices and Related Terahertz Spectroscopy Experiments, in PhD Thesis, IMEP-LAHC Laboratory, University of Grenoble, 2013, France.
[5] S.F. Zutavern, A.P. Glover, P.J. Foster, F.E. White, Extracting Dynamic Resistance from a Pulsed Power Switch with a Least Squares Approach, in Sandia National Laboratories Report SAND2013-4767C, 2013.
[6] W.A. Stygar, et al., Shaping the output pulse of a linear-transformer-driver module, Phys. Rev. Spec. Top.-Accel. 12 (2009) 030402.
[7] A. Mar, Electrical Breakdown Physics in Photoconductive Semiconductor Switches (PCSS), in Sandia National Laboratories 2015 LDRD Annual Report, 2015, pp. 213–214.
[8] Y. Shen, et al., A compact 300 kV solid-state high-voltage nanosecond generator for dielectric wall accelerator, Rev. Sci. Instrum. 86 (5) (2015) 055110.
[9] M. Östling, R. Ghandi, C.M. Zetterling, SiC power devices – present status, applications and future perspective, Proc. Int. Symp. Power 10-15 (2011).
[10] S. Sheng, et al., An investigation of 3C-SiC Photoconductive power switching devices, Mater. Sci. Eng. B-Adv. 46 (1997) 147–151.
[11] S. Porowski, Growth and properties of single crystalline GaN substrates and homoepitaxial layers, Mater. Sci. Eng. B-Adv. 44 (1997) 407–413.
[12] S.J. Pearton, J.C. Zolper, R.J. Shul, F. Ren, GaN: Processing, defects, and devices, J. Appl. Phys. 86 (1) (1999) 1–69.
[13] H. Amano, Progress and prospect of the growth of wide-band-gap group III nitrides: development of the growth method for single-crystal bulk GaN, Jpn. J. Appl. Phys. 52 (5R) (2013) 050001.
[14] E.A. Preble, et al., Single crystal group III nitride articles and method of producing same by hype method incorporating a polycrystalline layer for yield enhancement, US Patent No. US20100327291 A1 (2010).
[15] J.H. Leach, R. Metzger, E.A. Preble, K.R. Evans, High voltage bulk GaN-based photoconductive switches for pulsed power applications, Proc. SPIE 8625 (2013) 86251Z.
[16] V. Meyers, D. Mauch, J. Mankowski, J.C. Dickens, A.A. Neuber, Characterization of the optical properties of GaN:Fe for high voltage photoconductive switch applications, 2015 IEEE Pulsed Power Conference (2015).

[17] A. Malguth, Fe in III–V and II–VI semiconductors, Phys. Status Solidi (B) 245 (No. 3) (2008) 455–480.
[18] Y. Chen, H. Lu, D. Chen, F. Ren, R. Zhang, Y. Zheng, High-voltage photoconductive semiconductor switches fabricated on semi-insulating HVPE GaN:Fe template, Phys. Status Solidi (C) 13 (5–6) (2016) 374–377.
[19] X. Wang, S. Mazdumder, W. Shi, A GaN-based insulated photoconductive semiconductor switch for ultrashort high-power electric pulses, IEEE Electron Dev. Lett. 36 (2015) 5.
[20] D. Mauch, J. Dickens, V. Kuryatkov, V. Meyers, R. Ness, S. Nikishin, A. Neuber, Evaluation of GaN:Fe as a high voltage photoconductive semiconductor switch for pulsed power applications, IEEE Pulsed Power Conference (PPC) (2015).
[21] A.D. Koehlera, T.J. Anderson, A. Khachatrian, A. Nath, M.J. Tadjer, S.P. Buchner, K.D. Hobarta, F.J. Kuba, High voltage GaN lateral photoconductive semiconductor switches, ECS J. Solid State Sci.Technol. 6 (11) (2017) S3099–S3102.
[22] D. Mauch, C.h. Thomas, A. Neuber, J. Dickens, Overview of high voltage 4H-SiC photoconductive semiconductor switch efforts at Texas Tech University, IEEE Int. Power Modul. (2014) 23–27.
[23] M. Suproniuk, P. Kamiński, M. Pawłowski, R. Kozłowski, M.a. Pawłowski, An intelligent measurement system for characterisation of defect centres in semi-insulating materials, Prz. Elektrotechniczny 86 (11a) (2010) 247–252.
[24] M. Suproniuk, P. Kamiński, R. Kozłowski, M. Pawłowski, Effect of deep-level defects on transient photoconductivity of semi-insulating 4H-SiC, Acta Phys. Pol. A 125 (4) (2014) 1042–1048.
[25] M. Pawlowski, M. Suproniuk, The effect of model adequacy error of the correlation method for studies of defect centres by photoinduced transient spectroscopy, Prz. Elektrotechniczn 87 (10) (2011) 230–235.
[26] M. Suproniuk, P. Kaminski, M. Pawłowski, M. Wierzbowski, Current status of modelling the semi-insulating 4H-SiC transient photoconductivity for application to photoconductive switches, Opto-Electron. Rev. 25 (3) (2017) 171–180.
[27] J. Zutavern, et al., High-gain GaAs photoconductive semiconductor switches (PCSS): device lifetime, high-current testing, optical pulse generators, Proc. SPIE 2343 (1994) 146–154.
[28] W.C. Nunnally, D. Cooperstock, Methods and configurations for improving photo-conductive switch performance, Conference Record of the Twenty-Fifth International Power Modulator Symposium, 2002 and 2002 High-Voltage Workshop (2002) 183–186.
[29] G.J. Caporaso, S.E., Sampayan, J.S. Sulivan, D.M. Sanders, Optically-initiated silicon carbide high voltage switch, US Patent No. US8125089 B2 (2012).
[30] G.M. Loubriel, A.G. Baca, F. Zutavern, GaAs Photoconductive semiconductor switch, US Patent No. US5804815 (1998).
[31] A. Baca, et al., High gain photoconductive semiconductor switch having tailored doping profiles zones, US Patent No. US6248992 B1 (2001).
[32] A. Mar, et al., Doped contacts for high-longevity optically activated, high-gain GaAs photoconductive semiconductor switches, IEEE T. Plasma Sci. 28 (5) (2000) 1507–1511.
[33] G.J. Caporaso, Photoconductive switch package, US Patent No. US20140038321 A1 (2014).
[34] J.S. Sullivan, D.M., Sanders, S.A. Hawkins, S.E. Sampayan, High voltage photo switch package module, US Patent No. US8655125 B2 (2014).
[35] F.J. Mar, H.P. Zutavern, G.A. Vawter, R. Gallegos, Advanced high-longevity GaAs photoconductive semiconductor switches, in: Sandia National Laboratories Report SAND2015-3597C, 2015.
[36] F.J. Zutavern, et al., A compact, repetitive accelerator for military and industrial applications, in: Sandia National Laboratories Technical Report SAND98-0898, 1998.
[37] A. Mar, F.J. Zutavern, G. Loubriel, Multi-line triggering and interdigitated electrode structure for photoconductive semiconductor switches, US Patent No. US7173295 B1 (2007).
[38] R.S. Bhattacharya, H.B. Evans JR, Photoconductive semiconductor switch, US Patent No. US20140264684 A1 (2014).
[39] Kyma Website: http://www.kymatech.com/news/226-kyma-launches-their-first-device-product-the-ko-switch.
[40] SemiconductorToday Website: http://www.semiconductor-today.com/news_items/2015/nov/ues_271115.shtml.